AECL

RESEARCH REACTOR FUEL DEVELOPMENT AT AECL

by

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ABSTRACT

This paper reviews recent U_3Si_2 and U-Mo dispersion fuel development activities at AECL. The scope of work includes fabrication development, irradiation testing, post-irradiation examination and performance qualification. U-Mo alloys with a variety of compositions, ranging from 6 to 10 wt % Mo, have been fabricated with high purity and homogeneity in the product. The alloys and powders were characterized using optical and scanning electron microscopy, chemical analysis, and X-ray diffraction and neutron diffraction analysis. U-Mo powder samples have been supplied to the Argonne National Laboratory for irradiation testing in the ATR reactor. Low-enriched uranium fuel elements containing U-7 wt % Mo and U-10 wt % Mo with loadings up to 4.5 gU/cm^3 have been fabricated at CRL for irradiation testing in the NRU reactor. The U-Mo fuel elements will be tested in NRU at linear powers up to 145 kW/m, and to 85 atom % ^{235}U burnup.

1. INTRODUCTION

AECL has designed, fabricated, tested, and used fuels in research and power reactors for over 50 years. Currently, AECL manufactures low-enriched uranium (LEU, ~ 20% ^{235}U in U) fuel containing uranium silicide particles dispersed in aluminum for the NRU, MAPLE 1 and 2, and HANARO reactors. The NRU driver fuel element contains an Al-U_3Si metal-matrix-composite core loaded with 3.15 gU/cm^3. The cylindrical core is sheathed with finned aluminum cladding that is welded to aluminum end plugs.

The MAPLE fuel element design is based on the NRU and NRX fuel element designs. AECL began developing LEU fuel for the NRU and NRX reactors in the early 1980s, based on the considerable experience gained with U_3Si from earlier programs to develop high density fuel for CANDU reactors. By 1986, demonstration irradiations and post-irradiation examinations (PIE) of prototype NRU rods containing U_3Si dispersion fuel had been successfully completed at the Chalk River Laboratories (CRL) U_3Si was selected as the reference fuel+, with loadings of 3.15 gU/cm^3 for the NRU reactor and

+ The dispersed phase is used hereafter to identify the fuel; it is understood that the matrix is aluminum.

4.5 gU/cm^3 for the NRX reactor (NRX fuel development was terminated when AECL decided to shutdown the aging reactor).

When AECL began the design of the MAPLE reactors, the decision was made to base the MAPLE fuel design on the well-tested and highly successful fuels developed for the NRU and NRX reactors, scaled appropriately. Thus current MAPLE fuel assemblies also use finned fuel elements containing U_3Si fuel.

The LEU fuel is made in a modern fuel manufacturing facility that was designed, constructed, and commissioned at CRL between 1987 and 1990. The conversion of NRU to LEU fuel began in 1991 and was completed in 1993. To date, over 875 fuel rods (10500 elements containing approximately 2.2 T of U_3Si) have been used in NRU. Since the beginning of the prototype fuel test program in the 1980s, no fuel defects have been observed and no performance problems have been reported with the U_3Si fuel in NRU.

AECL also developed U_3Si_2 fuel to complement its U_3Si product line. U_3Si_2 powder is easier to make and fewer fuel fabrication steps are required compared to U_3Si. Mini-elements containing U_3Si_2 (3.15 gU/cm^3) were first fabricated and tested in the NRU reactor in 1987, and full-length, 3-m-long NRU prototype rods were irradiated in 1990 to qualify the fuel and the manufacturing process. The maximum element linear power achieved during the test irradiations was calculated to be ~92 kW/m. Post-irradiation examinations conducted in 1993 confirmed that U_3Si_2 performed well, and was suitable for use in AECL's research reactors.

The status of research reactor fuel development activities at AECL is described in this paper. Results from recent high-power U_3Si_2 test irradiations are presented, and the program to develop and qualify U-Mo dispersion fuel for MAPLE reactors is discussed.

2. U_3Si_2 FUEL DEVELOPMENT

AECL has selected U_3Si_2 as the reference fuel for the Canadian Neutron Facility (CNF, the planned replacement for the NRU reactor) and for future advanced MAPLE reactors that will operate at higher element linear powers than the MAPLE 1 and 2 reactors. Maximum ratings up to 120 kW/m are predicted for the CNF compared with 90 kW/m for MAPLE 1 and 2.

In order to demonstrate the high-power performance of U_3Si_2 fuel, a test irradiation of CNF mini-elements was undertaken in NRU. The objective of the irradiation was to demonstrate a suitable safety margin for the fuel during normal CNF operating conditions. It was recommended that the fuel should be tested at ratings at least 15% above the predicted maximum power, to accommodate any operational uncertainty. Mini-elements containing U_3Si_2 were fabricated at CRL. The typical mini-element design is described elsewhere [2]. The fabrication data are shown in Table 1.

Table 1. As-fabricated U_3Si_2 Mini-element.

Al-U_3Si_2 Mini-element Fuel Core Loading	**As-fabricated (measured and/or calculated)**
Core mass, g	18.4
Core density, g/cm^3	5.2
Porosity, vol %	2.8
U density in fuel, g/cm^3	3.1
Linear loading, gU/cm	1.0
Mass ^{235}U/cm solid core, g/cm	0.2

A test rod containing 16 U_3Si_2 mini-elements was flow tested and installed in the NRU reactor, and irradiation testing commenced in 1999 November. During the first phase of the irradiation to 20 atom % burnup, the mini-elements achieved a maximum fission power of 150 kW/m. The equivalent power density is 4.7 kW/cm^3. In the subsequent phases of the irradiation, the mini-elements operated at steadily declining power, to cover the test envelope. Figure 1 shows the power history of the U_3Si_2 fuel in NRU compared with the envelope (solid line) predicted for the CNF reactor, and the calculated power history for each cycle. At the time of writing (early 2000 September), the mini-elements had achieved ~70 atom % burnup, and the irradiation was continuing uneventfully.

Interim inspections were conducted after 20, 40, and 60 atom % burnup. Visual examinations and dimensional measurements confirmed that the mini-elements were intact and withstood the irradiations in satisfactory condition. There was evidence of higher-than-normal oxidation of the cladding over the heated surfaces, but this apparently did not breach the cladding nor compromise the fuel performance. Destructive PIE of the first mini-elements (20 atom % burnup) is scheduled to begin before 2000 December.

Uranium silicide dispersion fuels perform well in AECL's research reactors. However, no commercial organization currently offers reprocessing services for silicide fuels, even though the technical feasibility of silicide fuel reprocessing has been demonstrated at the US Savannah River facility and at the UKAEA facility in Dounreay. There is concern that reactor operators who do not have access to local storage or disposal facilities will face difficulty when the US spent fuel return policy expires in 2006. U-Mo fuel is an attractive option for such operators and for designers of the next generation of research reactors because it offers both an opportunity to close the fuel cycle through spent fuel reprocessing and a high U density to provide performance enhancements.

AECL continues to develop new fuel designs and new fuel cycle technologies, and has started on a new program to develop U-Mo fuel, as described below.

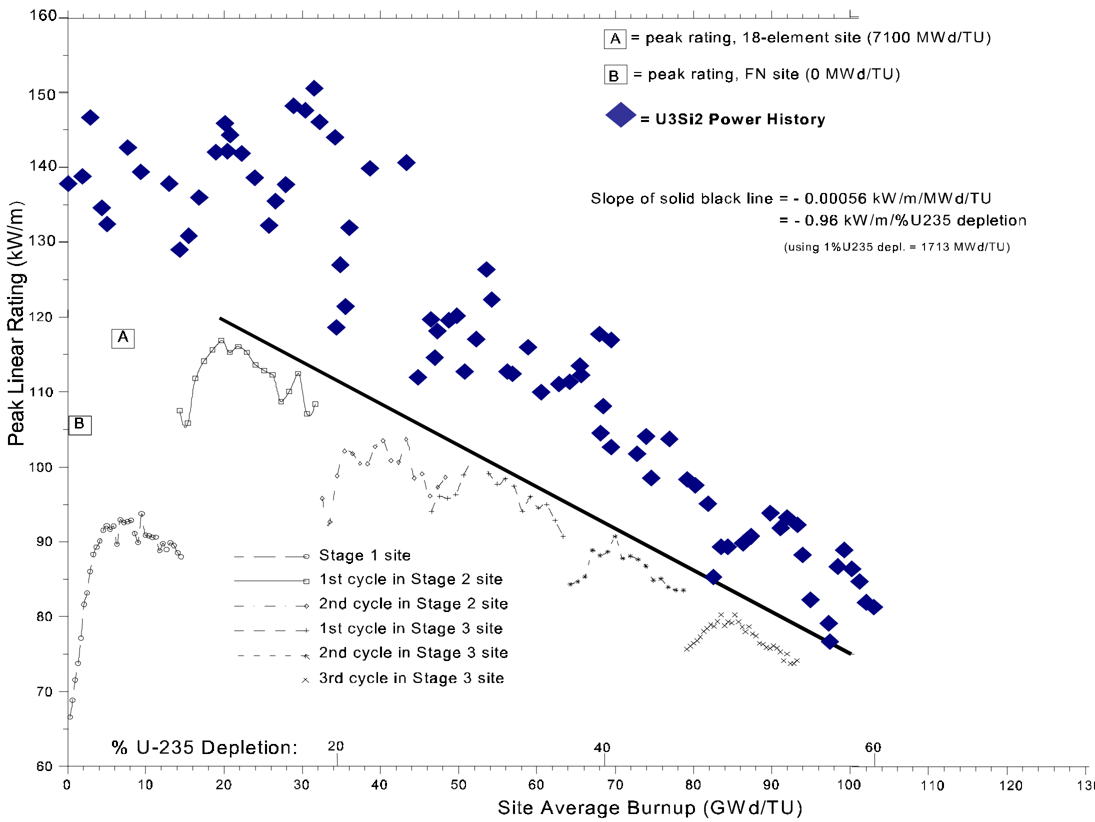

Figure 1. Power history of U_3Si_2 mini-elements compared with peak CNF fuel ratings.

3. U-Mo FUEL DEVELOPMENT

AECL has embarked on a fuel development program at CRL to qualify U-Mo dispersion fuel. The scope of work includes fabrication process development, irradiation testing, PIE, and performance verification. Initial assessments indicate that relatively straightforward modifications to the LEU silicide fuel fabrication facilities would be required because many of the production steps are common.

A phased approach has been adopted, based on earlier LEU fuel development experience. The first phase was focused on U-Mo alloy development, characterization and powder fabrication, and included collaboration with the US RERTR program. The second phase is focussed on LEU-Mo fuel element fabrication and irradiation testing in NRU.

3.1 U-Mo Alloy and Powder Fabrication

U-Mo dispersion fuel, like U-Si dispersion fuel, is made using powder metallurgy techniques. At AECL, the manufacturing process is essentially identical to that currently used for the NRU and MAPLE driver fuel—basically, the Al-UMo cores are extruded and machined to size, finned aluminum cladding is extruded over the cores, and the cladding is welded to the aluminum end plugs to hermetically seal the elements.

During the first phase of the program, we successfully fabricated U-Mo alloys with a variety of compositions, ranging from 6 to 10 wt % Mo. Figure 2 shows a photograph of the U and Mo materials in the crucible during the melting process. Figure 3 shows powder production in the inert atmosphere glovebox, and Figure 4 shows the typical morphology of the powders produced. The as-cast and heat-treated ingots and the powders were characterized using optical and scanning electron microscopy (SEM), chemical analysis, X-ray diffraction (XRD) and neutron diffraction analysis (NDA). The powders were checked to ensure that a homogeneous gamma phase existed after processing. The neutron diffraction pattern from a typical powder lot is shown in Figure 5, confirming that only the gamma phase was present. Samples of the powder have been supplied to the Argonne National Laboratory (ANL) for fabrication trials.

3.2 U-Mo Fuel Element Fabrication and Irradiation Testing

The development program demonstrated the technical feasibility of U-Mo fuel fabrication at AECL. Further confidence in the manufacturing processes was provided when LEU-Mo fuel elements were fabricated for irradiation testing in NRU.

A manufacturing plan, manufacturing procedures, and an inspection and test plan were developed for the campaign. Manufacturing was done to the maximum extent possible in the commercial LEU fuel fabrication facility. The production equipment was cleaned of U_3Si to prevent cross-contamination, then used to process LEU-Mo fuel.

The mini-element has been the standard test vehicle for irradiating research reactor fuel at AECL. To demonstrate the full scope of the manufacturing process, over 100 mini-elements were fabricated and inspected according to the QA requirements for the project. Mini-elements containing LEU-7Mo and LEU-10Mo with loadings up to 4.5 gU/cm^3 were fabricated for testing in NRU. Table 2 shows the nominal fabrication data for the U-Mo mini-elements.

Table 2. Nominal U-Mo Mini-Element Fuel Composition.

Al–U-Mo Mini-element Fuel Core Loading	**Al - 71.2 wt % U7Mo**	**Al - 72.4 wt % U10Mo**
Core density, g/cm^3	6.79	6.91
Core mass, g	24.0	24.5
U-Mo mass, g	17.1	17.7
U mass, g	15.9	15.9
U density in fuel, g/cm^3	4.5	4.5
Linear loading, gU/cm	1.4	1.4
Mass $^{235}U/cm$, g/cm	0.3	0.3

Two test rods containing U-7Mo and U-10Mo elements, and control elements containing U_3Si_2 will be irradiated in the NRU reactor. The U-Mo fuel elements will be tested at linear powers up to 145 kW/m, and to a discharge burnup of 85 atom % ^{235}U. The test irradiation is scheduled to start in 2000 September. Figure 6 shows U-Mo mini-elements selected for the test irradiation in NRU.

3.3 Optional Higher Density U-Mo Fuel Development

The immediate goal is to develop U-Mo fuel with 3.15 to 4.5 gU/cm^3, to facilitate the direct substitution of U-Mo fuel for U_3Si or U_3Si_2 fuel in MAPLE reactors by demonstrating acceptable performance of U-Mo fuel with equivalent or slightly higher fissile loadings. Currently, U-Si is the reference fuel for the NRU, HANARO, MAPLE 1 and 2, and CNF reactors. Some of these reactors have been optimized to use U-Si fuel, but it is likely that they could also use U-Mo with "equivalent" fissile loadings to compensate for the higher capture cross-section of Mo compared with Si. A numerical study conducted at ANL on a simplified research reactor indicated that at a dispersant volume fraction of 50%, the loss in fuel cycle length from parasitic absorption is 4.3% and 10%, respectively, for U-Mo (5%) and U-Mo (9%), compared with U_3Si_2. To recover such a loss in a future MAPLE design would require increasing the uranium loading density by 1.7% and 3.9%, respectively. From the ANL study, this loading increase leads to a small decrease in the reflector thermal flux (and hence in user facility performance) of 0.2% and 0.4%, respectively; i.e., essentially equivalent performance.

The MAPLE reactors currently use a much lower fuel loading than that considered in the above study, nominally 3.15 gU/cm^3, i.e, 21 vol % U_3Si or 28 vol % U_3Si_2. It was decided that U-Mo fuel with 4.5 gU/cm^3 should be tested for the CNF and future MAPLE reactors. This higher density would yield higher fissile loadings in the bundles. The higher fissile loading could be used to extend the time between refueling or to compensate for higher parasitic reactivity loads in experiments. A higher fissile loading could also be used to reduce the refueling requirements for a fixed operating cycle, thereby reducing the fuel cycle costs. If the fuel were to be reprocessed, back-end costs could be reduced because the spent fuel management costs are nominally proportional to the quantity of assemblies used.

To take optimum advantage of even higher uranium densities requires reducing the fuelled volume of the core to increase fluxes and leakage to the reflector. However, a means of dealing with the higher excess reactivity and qualification of the fuel for higher power ratings would be required. Specific changes for performance uprating may require qualification tests, demonstration irradiations, and safety and licensing assessments for each reactor and fuel design. Therefore U-Mo fuel with densities higher than 4.5 gU/cm^3 will be developed only if the cost–benefit analysis shows a clear and compelling advantage.

3.4 Future Work

It is expected that irradiation testing in NRU will be completed by the spring of 2002. After an adequate cooling period, detailed PIE will be done to confirm that the U-Mo fuel performance is consistent with expectations based on our experience with LEU dispersion fuels. The results will be documented to qualify the fuel for use in MAPLE reactors.

The U-Mo program follows the proven approach that was successfully employed in the development of uranium silicide fuels and builds on the experience that AECL has gained with other fuel programs.

4. SUMMARY

- AECL's U_3Si dispersion fuel continues to perform satisfactorily in the NRU and MAPLE-type reactors.
- U_3Si_2 fuel has been selected for the proposed CNF reactor, and irradiations are nearing completion in NRU to qualify the U_3Si_2 fuel for very high-power applications. The U_3Si_2 mini-elements have achieved a maximum element linear power of 150 kW/m, and a current burnup of 70 atom % ^{235}U.
- AECL has a proven fuel development track record, and continues to develop new fuels and fuel cycles for research reactors. A new U-Mo fuel development program is underway at CRL. Alloys with compositions ranging from U-6 wt % Mo to U-10 wt % Mo have been fabricated. Powders have been produced from the alloys and characterized using optical and SEM metallography, chemical analysis, X-ray diffraction, and neutron diffraction analysis.
- LEU-10Mo and LEU-7Mo mini-elements have been fabricated with loadings of 4.5 gU/cm^3 for a test irradiation in NRU. The irradiation is scheduled to start in 2000 September, and is expected to achieve the target 85 atom % ^{235}U burnup by the spring of 2002.
- AECL's fuel fabrication facility currently supplies LEU fuel to the NRU, HANARO and MAPLE 1 and 2 reactors. It has been demonstrated that U-Mo fuel could be manufactured in the same facility at CRL.

5. REFERENCES

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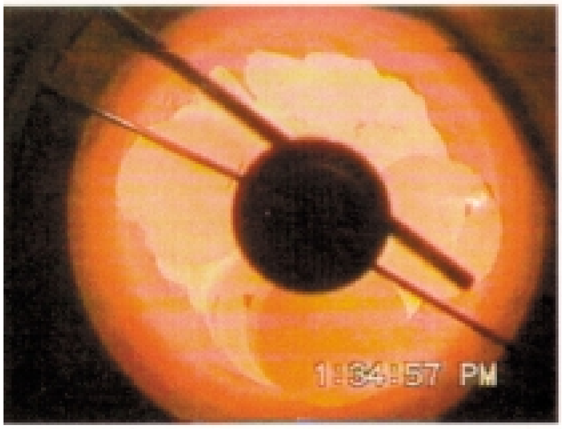


Figure 2. Photo of U and Mo in Crucible During Melting.

Figure 3. U-Mo Powder Fabraction in Glovebox at Chalk River.

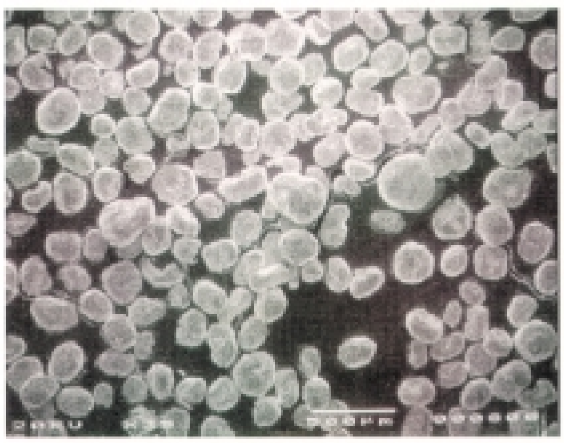


Figure 4. SEM Image of U-10wt%Mo Powder.

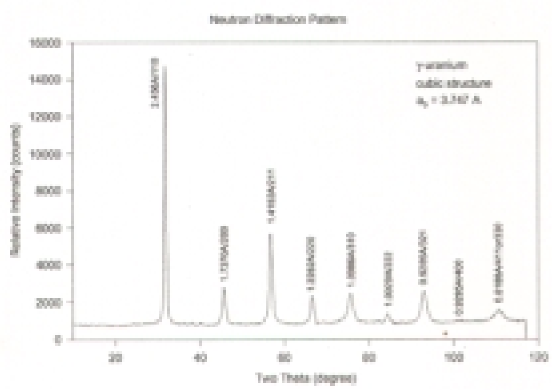
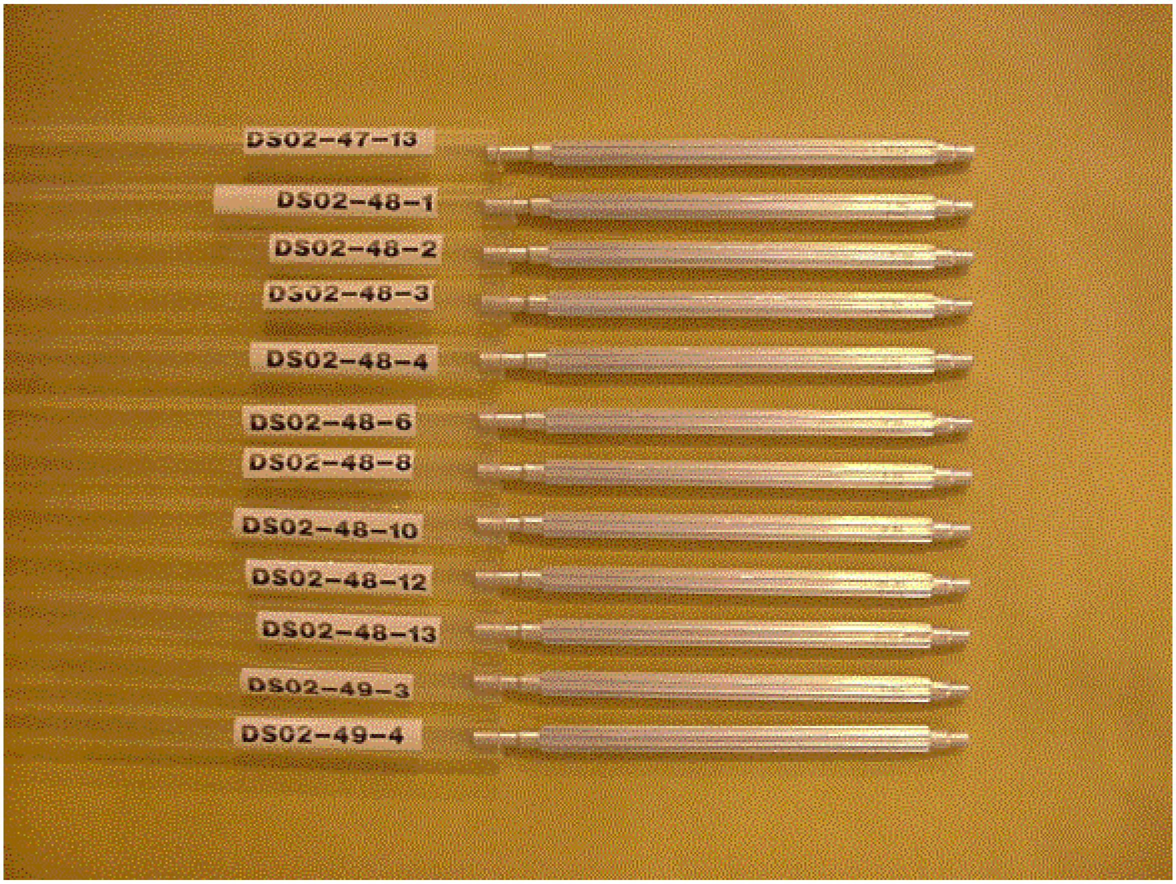


Figure 5. Neutron Diffraction Pattern from U-Mo Powder.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